Optical Diagnostics for Extreme Beam Conditions

Ralph B. Fiorito

University of Liverpool/ Cockcroft Institute; University of Maryland/ IREAP
OUTLINE

Terminology:  Optical: mostly visible, but some stretch (UV – THz)
Extreme: $\sigma_r, \varepsilon \leq \mu m$, $\sigma_z \sim \lambda$, $\chi \approx 1$, DR $> 10^5$

Emphasis: Diagnostic methods that are generally applicable (linacs, synchrotrons, PWAs),
simple, low cost, minimally invasive and potentially single shot.

Observables:

1) Imaging using the single particle function (SPF) of incoherent ($\lambda \ll c\Delta\tau$) beam associated radiation, e.g. OTR, OSR, phosphorescence
   a. OTR SPF dependence on beam size
   b. Low energy OTR calculations of SPF + new algorithm which includes $\Delta\lambda$
   c. OSR Line spread function
   d. LSYO scintillator, 1 micron measurement

2) High dynamic range imaging: DR $\sim 10^6$
   a) DMD imaging
   b) measurements of PSF with/wo DMD

3) RMS beam size measurements using interference methods
   a) ODRI from two slits separated longitudinally
   b) OSR from two pinholes separated transversely (1D or 2D)
   c) OSRI from multiple slit diffractive element, optical and UV
• **Emittance (transverse)**

Size + divergence measurement techniques applicable to beams with high space charge

a) modified quad scan (beam size + divergence vs 1/f) → $<rr'> \rightarrow \epsilon_{rms} \leq 1 \mu m,$

b) OPSM methods (optical pepper pot technique) using OTR
   1- optical pinhole scanning / mechanical and electronic scanning with DMD
   2- micro-lens array method (single shot)

• **Bunch length:** single shot, use coherent optical radiation ($\lambda \geq c\Delta \tau$), e.g. CTR and CDR

Angular/spatial distribution (SPF) imaging, $cT \sim \lambda = (1 \mu m - 1 mm)$
Using the Single particle Function (SPF) of OTR to measure very small (submicron) beams


Beam size: OTR SPF

OTR image
KEK ATF2
e beam
1.3 GeV

minimum measured vertical beam size: \(0.754 \pm 0.034 \ \mu\text{m}\)
High resolution images indicate that large bandpass may be tolerable without significantly deteriorating visibility

40 nm Interference Filter

no Interference Filter

M=1

M=1
Study of Effect of Bandpass on OTR SPF Minimum

![Graph showing the effect of bandpass on OTR SPF minimum.](image-url)
Energy Scaling in OTR Calculations: Reduces Computational Requirements*

*See: J. Wolfenden, et. al., paper WEPAF036 for more details
Theory Based Algorithm to Determine Beam Size using OTR single particle SPF*

OTR single particle SPF

Zemax Optical Studio includes real optics effects aberrations, offsets, etc.

Source Model

Optics Propagation

Beam Distribution Convolution

\( \theta_m, \lambda \)

\( \lambda \)

\( \sigma \)

Compare to measurements, best fit \( \sigma_{\text{rms}} \)

\( \lambda \) loop

\( \sigma \) loop
Beam Size determination by deconvolution of the OSR SPF or “filament beam spread function” (FBSF)*

Beam size: OSR FBSF

*. Andersson, 60th ICFA Advanced Beam Dynamics Workshop FLS2018, Shanghai March 5-9.
Resolving vertical beam sizes $< 5 \mu m$ using Visibility and Shape of Pi polarized SPF

\[ \sigma_y = 5 \mu \]
High Resolution Scintillator Studies using Single Particle (Line Spread) Function*

Target: LYSO scintillator \((\text{Lu}_{2(1-x)}\text{Y}_{2x}\text{SiO}_5;\text{Ce})\)

- thickness \(t = 200 \, \mu\text{m}\)
- supplier: OmegaPiezo

Imaging Optic: Schwarzschild Objective:
- 2 concentric spherical mirrors
- aplanatic (corrected for spherical aberrations)
  - \(f = 26.90 \, \text{mm}\)
  - \(NA = 0.19\) (nominal)

Micrometer beam size experiment at MAMI**

- \(a = 27.54 \, \text{mm}\)
- \(b = 1155.46 \, \text{mm}\)
- \(M = 41.95\)

** G. Kube, S. Bajt, A.P. Potylitsyn, et. al., Proc. IBIC2015, Melbourne, Australia

*G. Kube, DESY, Workshop on Emittance Measurements, ALBA, Jan 2018
Beam size determination via Convolution of Gaussian with Scintillator SPF

**Analysis:** scintillator model in Zemax

- light emission from single electron represented by line source in LYSO crystal with isotropic light emission
- scintillator properties described by $n(\lambda)$
- Schwarzschild objective (used in experiment) replaced by paraxial lens with same $f$ and $NA$
- non-sequential ray tracing for $10^8$ rays at LYSO peak emission wavelength $\lambda = 420$ nm
- single particle source function (SPF)

Convolution of SPF with 2D-Gaussian model for beam

To improve resolution reduce $t$
High Dynamic Range Imaging system using DMD

Advantages/ Disadvantages
1. Each mask only requires limited DR image
2. Most scattered light from the core is eliminated - extinction ~10^3
3. Core and Halo can be monitored at same time

H. Zhang, R. Fiorito, et. al. PRSTAB, 2012; J. Egberts and C. Welsch, JINST, 2010
Halo Imaging of JLAB CW beam with OSR and DMD*

(R = 0.63 mA, 4.68MHz, 135pc/micropulse, $\lambda = 654nm \times 90nm$, ND=0.4)

Optical Diffraction Radiation Interferences: sensitive to $\sigma, \sigma'$

ODRI from two collinear slits

N.B.: slit separation, $L \ll L_{coh} \sim \gamma^2 \lambda$

ODRI from two non-collinear slits

A 50 $\mu$m offset between the slits removes the mixing between $\sigma, \sigma'$

Quad scan and emittance determination using ODRI data

1 GeV
20 pulses
200 pC/pulse
10 Hz
2 s CCD integration time
=> 80 nC integrated charge

$\varepsilon_y^{ODRI} = (2.23 \pm 0.85)$ mm-mrad
$\varepsilon_y^{OTR} = (2.37 \pm 0.46)$ mm-mrad

UV DRI Experiments at KEK- ATF2*

Diffraction Radiation interference (DRI) from target slit (49.57 μm) and mask slit (100 μm) observed in visible (400nm) and UV (250nm) thanks to intensified cameras.

Single shot UV DRI

Vertical scan of DRI

Quad scan

Visibility

Current [Amps]

Visibility

σ_y (microns)

I_{max} / I_{min}

M. Bergamaschi\textsuperscript{1,2}, A. Aryshev\textsuperscript{3}, P. Karataev\textsuperscript{1}, R. Kieffer\textsuperscript{2}, T. Lefevre\textsuperscript{2}, S. Mazzoni\textsuperscript{2}

CLIC Workshop 2018, CERN, 23rd January 2018

* V = \frac{I_{max}}{I_{min}}
Beam Shape Reconstruction using OSR interferometry*

OSRI beam size measurement along direction of pinholes**

\[
I = I_0 \left\{ \frac{J_1\left(\frac{2\pi ax}{\lambda f}\right)}{\left(\frac{2\pi ax}{\lambda f}\right)} \right\}^2 \times \left\{ 1 + V \cos \left(\frac{2\pi Dx}{\lambda f}\right) \right\}
\]

\[
\sigma_x = \frac{\lambda L}{\pi D \sqrt{\frac{1}{2} \ln \frac{1}{V}}}
\]

**T. Mitsuhashi, Proc. of IPAC15

*L. Torino, Workshop on Emittance Measurements, ALBA, Jan. 2018
Theoretical fit produces good estimate of small beam sizes with fewer data points.

Rotation of pinholes allows measurement of projections of beam parallel and perpendicular to pinhole axis.

Theoretical fit produces good estimate of small beam sizes with fewer data points.
OSRI Use of Diffraction Obstacle to Resolve a Vertical Beam size < 3 μm*

This diffractometer method was implemented at the SLS (TIARA collaboration): $\sigma_y = 4.7 \pm 0.1 \mu m**$

now being used routinely at MAXIV

Novel Quad Scan Method to Determine the rms Emittance of a Space Charge Dominated Beam*

Method:

- Measure rms beam size ($\sigma$) and rms divergence ($\sigma'$) at least two values of magnetic focusing strengths ($1/f$).
- Use envelop equation to compute cross-correlation term in the equation for the rms emittance: \[ \varepsilon = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2} \] in terms of ($\sigma, \sigma'$).

Advantages:

- Doesn’t need a complete quadrupole or solenoid scan
- Multiple ($\sigma, \sigma'$) data pairs increase statistical accuracy of measurement
- Works for space charge or emittance dominated beams

*K. Poorrezaie, R. Fiorito, et. al., PRAB 2013
Experiments/Simulations at ANL (AWA) to Validate New Method*

Results to date:

OPAL simulations

Tomography

\[ e_x = 8 - 9 \text{ micron} \]

\[ e_x = 8.4 \text{ micron} \]

* R. Fiorito, et. al. Proc. IPAC17
Optical Phase Space Mapping: optical replica of the standard pepper pot collimator method

Advantages:

- No physical collimation of beam particles necessary
- Minimally invasive (OTR) to non invasive (ODR, OSR)
- Only optical considerations needed
- Zemax can be used to optimize design

Standard PSM
Optical phase space mapping demonstrated with a fixed and movable pinhole masks*

* G. Le Sage, R. Fiorito, et. al., PRAB (1999); R. Fiorito, et. AIP Conf. Proc. 648, (2002);
Current Work: Optical Phase Space Mapping with a Programmable mask using DMD

Status and Plans
- implement Zemax to model DMD based OPSM system
- study effects of mask size, shape on resolution of the imaging system (PSF);
- build and test performance of OPSM at a real accelerator using OTR or OSR.
OPSM Emittance Measurement Using a Micro-lens Array *


* A. Cianchi, Workshop on Emittance Measurements, ALBA, Jan. 2018
Novel Bunch Length Monitor Using Angular/Spatial Distributions of Coherent Diffraction Radiation*

- Spectra of CTR and CDR typically used as a measure of bunch length
- Angular and Spatial Distributions of CDR also sensitive to bunch length

\[
\frac{dI_{bunch}^{CDR}}{d\Omega} \approx N_e^2 \int_{\Delta\omega} \frac{d^2 I_e^{DR}}{d\omega d\Omega} S_z(\sigma_z, \omega) d\omega
\]

Spectral-Angular Distribution of DR from a single electron

Longitudinal form factor

*A. Shkvarunets and R. Fiorito, PRSTAB, (2008)
Advantages of CDR Imaging Bunch Length Monitor:

- No wide band spectral measurements or Fourier transformations necessary
- Single Shot
- Non invasive
- Simple to experimentally implement

Procedure:

- Choose the size and shape of the radiator so that CDR intensity is sensitive to the range of bunch sizes under investigation \((1/\Delta \omega \sim \Delta \tau)\)
- Use theory/simulation code to predict the frequency integrated AD and SPF
- Use appropriate imaging optics and detector to view AD and SPF e.g. for pico-fsec bunches use GHz-THz transmissive optics and pyroelectric sensor
- Fit measured images to theory to measure rms bunch length
Angular Distribution Experiment Confirmation

Scans of AD of CTR and CDR from 100 MeV RF Injector Linac (PSI- SLS)

<table>
<thead>
<tr>
<th>Method</th>
<th>Bunch Compressor Tune</th>
<th>T(ps) single Gaussian fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>AD CDR</td>
<td>PBU-0</td>
<td>0.8</td>
</tr>
<tr>
<td>E-O technique</td>
<td>PBU-0</td>
<td>0.75</td>
</tr>
<tr>
<td>AD CDR</td>
<td>PBU+3</td>
<td>1.0</td>
</tr>
<tr>
<td>E-O technique</td>
<td>PBU+3</td>
<td>1.0</td>
</tr>
</tbody>
</table>

CDR Spatial Distribution Measurements

Advantages:
1- Less interference from upstream sources, especially at high energy where \( L \approx \gamma^2 \lambda \) large (e.g. 40 km for 1 THz at 20 GeV)
2- More intense than angular distribution (more photons per pixel)
3- Easier to focus and setup optics

Results: SLAC-FACET (April 2016)
Theoretical (inverted) horizontal scan of CDR from FACET (20 GeV)

\[
\text{cdT} = 25 \text{ micron}
\]

\[
Q = 0.6 \text{ nC}
\]

\[
\sigma = 150 \text{ microns}
\]

Peak to peak separation of experimental scan is almost 2 X theory => focusing error \( \rightarrow \) Need follow up experiment to check
Possible Detectors
1) Pyroelectric single element
2) Linear Array (need high sensitivity <~ 1 nJ/pixel)
3) Pyrocam (S_{min} ~ 7 nJ/pixel)

Optical Setup
- IR laser
- Alignment mirror
- Polarizer
- Silicon window
- THz lens
- Linear actuator (scanning)
- Iris + detector
- Linear actuator (focusing: near field-farfield)

Calculated CDR SPF’s for 0.5, 1.0 and 1.5 ps bunch lengths (peak Amplitudes: 4.6E-5 5.2E-6 8.7E-7)

*See: J. Wolfenden, et. al., paper WEPAF035 for more details
Acknowledgements

Colleagues:

- Cockcroft Institute:
  University of Liverpool: J. Wolfenden, H. Zhang, C. Welsch
  University of Manchester: T. Pacey, O. Mete
  ASTEC: D. Walsh, M. Surman, R. Smith

- University of Maryland: A. Shkvarunets
- Paul Scherrer Institute (SwissFEL): R. Ischebeck, G. Orlandi, F. Frei, N. Hiller, S. Bettoni
- SLAC (FACET): C. Clarke, A. Fisher; (SPEAR3): J. Corbett
- KEK: A. Aryshev, T. Mitsuhashi, N. Terunuma
- RHUL (John Adams Institute), P. Karataev, K. Kruchinin (now at ELI Beam lines)
- CERN: M. Bergamaschi, T. Lefevre, S. Mazzoni, R. Kieffer
- MAXIV: A. Andersson
- INFN LFN: A. Cianchi, E. Chiadroni, F. Bisesto
- DESY: G. Kube
- ALBA: L. Torino (now at ESRF), U. Ariso

Sponsor: European Union: Marie Curie Sr. Fellowship hosted by U. Liverpool/Cockcroft*

* Information on EU sponsored PhD Training Networks and Fellowships
  see: University of Liverpool - Exhibit Hall – Table 400